Consensus for experimental design in electromyography (CEDE) project

Besomi, Manuela; Hodges, Paul W.; Clancy, Edward A.; Van Dieën, Jaap; Hug, François; Lowery, Madeleine; Merletti, Roberto; Søgaard, Karen; Wrigley, Tim; Besier, Thor; Carson, Richard G.; Disselhorst-Klug, Catherine; Enoka, Roger M.; Falla, Deborah; Farina, Dario; Gandevia, Simon; Holobar, Aleš; Kiernan, Matthew C.; McGill, Kevin; Perreault, Eric

published in
Journal of Electromyography and Kinesiology
2020

DOI (link to publisher)
10.1016/j.jelekin.2020.102438

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

Journal of Electromyography and Kinesiology 53 (2020) 102438

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Consensus for experimental design in electromyography (CEDE) project: Amplitude normalization matrix

Manuela Besomi[a], Paul W. Hodges[a,*], Edward A. Clancy[b], Jaap Van Dieën[c], François Hug[a,d,e], Madeleine Lowery[f], Roberto Merletti[g], Karen Søgaard[h], Tim Wrigley[i], Thor Besier[j], Richard G. Carson[k,l,m], Catherine Disselhorst-Klug[n], Roger M. Enoka[o], Deborah Falla[p], Dario Farina[q], Simon Gandevia[r], Aleš Holobar[s], Matthew C. Kiernan[t,u], Kevin McGill[v], Eric Perreault[w,x], John C. Rothwell[y], Kylie Tucker[a,z]

[a] School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Australia
[b] Worcester Polytechnic Institute, Worcester, MA, USA
[c] Department of Human Movement Sciences, Vrije Universiteit Amsterdam, Amsterdam Movement Sciences, Amsterdam, the Netherlands
[d] Faculty of Sport Sciences, Laboratory "Movement, Interactions, Performance" (EA 4334), University of Nantes, Nantes, France
[e] Institut Universitaire de France (IUF), Paris, France
[f] School of Electrical and Electronic Engineering, University College Dublin, Dublin, Ireland
[g] LISiN, Department of Electronics and Telecommunications, Politecnico di Torino, Torino, Italy
[h] Department of Clinical Research and Department of Sports Science and Clinical Biomechanics, University of Southern Denmark, Odense, Denmark
[i] Centre for Health, Exercise and Sports Medicine, Department of Physiotherapy, University of Melbourne, Parkville, Australia
[j] Auckland Bioengineering Institute and Department of Engineering Science, University of Auckland, Auckland, New Zealand
[k] Trinity College Institute of Neuroscience, School of Psychology, Trinity College Dublin, Dublin, Ireland
[l] School of Psychology, Queen's University Belfast, Belfast, UK
[m] School of Human Movement and Nutrition Sciences, The University of Queensland, Australia
[n] Department of Rehabilitation and Prevention Engineering, Institute of Applied Medical Engineering, RWTH Aachen University, Aachen, Germany
[o] Department of Integrative Physiology, University of Colorado Boulder, CO, USA
[p] Centre of Precision Rehabilitation for Spinal Pain (CPR Spine), School of Sport, Exercise and Rehabilitation Sciences, University of Birmingham, UK
[q] Department of Bioengineering, Imperial College London, London, UK
[r] Neuroscience Research Australia, University of New South Wales, Sydney, Australia
[s] Faculty of Electrical Engineering and Computer Science, University of Maribor, Koroška cesta 46, Maribor, Slovenia
[t] Brain and Mind Centre, University of Sydney, Sydney, Australia
[u] Department of Neurology, Royal Prince Alfred Hospital, Sydney, Australia
[v] US Department of Veterans Affairs, USA
[w] Northwestern University, Evanston, IL, USA
[x] Shirley Ryan AbilityLab, Chicago, IL, USA
[y] Sobell Department of Motor Neuroscience and Movement Disorders, UCL Institute of Neurology, London, UK
[z] School of Biomedical Sciences, The University of Queensland, Brisbane, Australia

ARTICLE INFO

Keywords:
Electromyography
Muscle activation
Amplitude normalization
Consensus

ABSTRACT

The general purpose of normalization of EMG amplitude is to enable comparisons between participants, muscles, measurement sessions or electrode positions. Normalization is necessary to reduce the impact of differences in physiological and anatomical characteristics of muscles and surrounding tissues. Normalization of the EMG amplitude provides information about the magnitude of muscle activation relative to a reference value. It is essential to select an appropriate method for normalization with specific reference to how the EMG signal will be interpreted, and to consider how the normalized EMG amplitude may change when interpreting it under specific conditions. This matrix, developed by the Consensus for Experimental Design in Electromyography (CEDE) project, presents six approaches to EMG normalization: (1) Maximal voluntary contraction (MVC) in same task/context as the task of interest, (2) Standardized isometric MVC (which is not necessarily matched to the contraction type in the task of interest), (3) Standardized submaximal task (isometric/dynamic) that can be task-specific, (4) Peak/mean EMG amplitude in task, (5) Non-normalized, and (6) Maximal M-wave. General considerations for normalization, features that should be reported, definitions, and "pros and cons" of each

* Corresponding author at: School of Health and Rehabilitation Sciences, The University of Queensland, Brisbane, Qld 4072, Australia.
E-mail address: p.hodges@uq.edu.au (P.W. Hodges).

https://doi.org/10.1016/j.jelekin.2020.102438
Received 9 April 2020; Received in revised form 3 June 2020; Accepted 5 June 2020

normalization approach are presented first. This information is followed by recommendations for specific experimental contexts, along with an explanation of the factors that determine the suitability of a method, and frequently asked questions. This matrix is intended to help researchers when selecting, reporting and interpreting EMG amplitude data.

1. Introduction

The estimation of the degree of muscle activation is one of the most common applications of electromyographic (EMG) recordings. Although the terms "muscle activation" and "EMG amplitude" are often used interchangeably, they represent different concepts. *Muscle activation* refers to the number of muscle fibers activated and their firing rates. *EMG amplitude* relates to the time-varying standard deviation of the EMG signal associated with the transmission of action potentials along the muscle fiber membranes. The raw interferential EMG signal is a noise-like signal. Although its amplitude is related to the level of muscle activation, the precise nature of the relationship is affected by many factors (Farina et al., 2004, 2014; Raez et al., 2006). To analyze and interpret EMG amplitude data, normalization is usually needed (Staudenmann et al., 2010).

The purpose of EMG amplitude normalization is to enable comparisons between participants, muscles, measurement sessions or electrode positions by accounting for features that would influence the amplitude of the EMG signal, and thus alter the nature of its relationship to muscle activation. These features include physiological and anatomical characteristics of muscles and surrounding tissues that could/would differ between muscles, study participants and testing sessions (e.g., distribution and number of fibers in the motor unit territories, orientation of the muscle fibers, thickness of the subcutaneous tissue layers, spatial organization of the innervation zone), and characteristics of the detection system (e.g., properties of the electrode-tissue interface, inter-electrode distance, orientation relative to muscle fibers) (Burden, 2010). For any recording situation, it is generally not possible to quantify the contribution of each of these factors to variation in EMG amplitude. This makes it difficult to interpret the absolute value of the EMG signal amplitude.

In principle, the normalized EMG amplitude value provides information about the degree of muscle activation present in a specific task context, expressed relative to a reference value used for normalization. Various normalization methods have been described (Burden, 2010; Merlo and Campanini, 2016), such as the reference to a maximal voluntary contraction (MVC), sub-maximal voluntary contraction, peak/mean during task, etc. Although normalization to an MVC is commonly used, because it is generally repeatable and provides a reference value that can be interpreted easily, i.e., relative to the maximum possible activation of the muscle (Bolgla and Uhl, 2007; Burden, 2010), this is not always possible and may not be the best method for some needed analyses (Hug and Tucker, 2017). Although some methods have been reported as reliable (Albertus-Kajee et al., 2011; Murley et al., 2010; Tabard-Fougere et al., 2018) and give similar values between sessions, this does not ensure that the normalized EMG amplitude value enables a valid comparison of the level of activation of a muscle(s) for a specific application or research question. It is important to consider whether the normalization method is both repeatable *and* valid, and suitable to answer the specific question being addressed with EMG. Accurate interpretation of EMG data depends on the appropriate selection of the amplitude normalization method and this should be well justified.

Several guidelines and recommendations provide guidance regarding methodological issues of EMG, such as the SENIAM project (European Recommendations for Surface Electromyography) (Hermens et al., 2000), and the EMG reporting standards (International Society of Electrophysiology and Kinesiology) (Merletti, 2014). These guidelines address some aspects of the EMG experimental design, but neither provides clear guidance for decision making with respect to the question being addressed by the application of EMG in research or clinical practice. This is important as different normalization methods may be appropriate/inappropriate for specific applications. Advice regarding the appropriateness of a normalization method for a specific context is not straight-forward. Although some recommendations are based on clear empirical evidence, many scenarios have not been addressed and recommendations depend on expert knowledge. Further, in some task contexts or in some participant groups (e.g., people with pain, children, etc.), the optimal method for EMG normalization may not necessarily be possible or practical. In such circumstances, decisions that are made concerning the means of analyzing and interpreting EMG amplitude may be guided usefully by recommendations from and, ideally consensus among, expert practitioners. The Consensus for Experimental Design in Electromyography (CEDE) project aims to provide expert consensus to guide decision-making in the recording, analysis, and interpretation of EMG (Hodges, 2019), and with specific reference to guidance for specific applications. Recommendations are presented as matrices that guide the application and interpretation of different salient features of EMG. The present CEDE matrix was developed to summarize recommendations for the normalization of EMG amplitude. The information presented in this document generally can be related to the rectified, smoothed EMG signal.

2. Methods

Details of the project, including the method for expert group selection, and the process for the development of the CEDE matrices have been described in detail elsewhere (Besomi et al., 2019; Hodges, 2019). In brief, a three-step process was followed in preparation of this matrix: (1) Development of the draft content by a steering committee from the CEDE project; (2) General comments from CEDE team members with expertise in the topic; and (3) A Delphi process to reach consensus of the content. Participants of the Delphi process are co-authors. Approval for this project was obtained from the Human Research Ethics Committee of The University of Queensland, Australia.

2.1. Development of the draft content by the steering committee and CEDE project team

Draft content for the matrix was developed by the steering committee (MB, PWH) and CEDE project team members with expertise in this topic (EAC, JVD, FH, ML, RM, KS, TW). The content was prepared with consideration of the advantages and limitations of each EMG amplitude normalization method. Six methodological approaches to normalization of EMG amplitudes were considered in the matrix: (1) MVC in same task/context as the task of interest (with matched contraction type, muscle length/joint angle, and/or velocity), (2) Standardized isometric MVC (which is not matched to the contraction type, muscle length/joint angle, and/or velocity of the task), (3) Standardized submaximal task (isometric/dynamic) that can be task-

Table 1
Descriptors used to identify the appropriateness of a normalization approach.

Descriptor	Definition
YES	High probability that it is appropriate
CAUTION	Might be appropriate but with consideration of specific issues
GENERALLY NO	Generally not appropriate, but may be accepted with consideration of specific issues
NO	High probability that it is inappropriate

Table 2
EMG amplitude normalization matrix.

General considerations for normalization

Purpose of normalization
The purpose of EMG amplitude normalization is to better enable comparisons between participants/muscles/measurement sessions/electrode positions by accounting for differences in physiological/anatomical characteristics of muscles and surrounding tissues, within and between individuals. In addition to the level of activation of the muscle, EMG amplitude is influenced by factors such as muscle size, distance and orientation of the electrode relative to active muscle fibers, electrical characteristics of the intervening tissue including subcutaneous fat thickness, properties of the electrode-tissue interface and possible variation in size of motor unit action potentials between muscles and individuals. It is generally not possible to estimate the contribution of these factors accurately in any particular recording situation, which makes it difficult to interpret the absolute value of the EMG signal amplitude. Normalization of the EMG amplitude to a reference value provides information about the relative magnitude of muscle activation (relative to its maximum produced at 100% maximum voluntary contraction of that muscle or to other reference), and estimates the distribution of the activation among the muscles involved in a motor task expressed as % of EMG amplitude with respect to a reference. It is essential to select an appropriate method for normalization with specific reference to how the EMG signal will be interpreted and to consider how this relationship may change when interpreting EMG amplitude under dynamic conditions. Factors other than neural drive and muscle activation that impact EMG amplitude (as detailed above) affect all normalization techniques, especially if the distribution of the muscle fibers (orientation and location) activated at the normalized task differ from the fibers that are activated under the task of investigation. It is important to note that amplitude normalization does not eliminate crosstalk from neighbor muscles, and should not be used with that purpose. Signal processing should be identical for the task and the reference task used for normalization.

Normalization to maximum voluntary contraction (MVC)
Normalization to the maximal EMG amplitude during an MVC is often recommended, because it provides a reference that is generally repeatable and normalization to this value, under the same conditions, may be interpreted as the percentage of the maximal activation of the muscle. This method, in turn, can provide an approximate estimate of the proportion of the muscle's potential force output **assuming a linear relation** between activation and force (**although the relationship is not always linear**). The normalized EMG only indicates the amount of activation relative to the muscle's maximal potential activation (as determined by the MVC protocol), but not the muscle's absolute contribution to the generated joint torque (i.e., a small and large muscle can both be activated to 100% but produce vastly different absolute forces). Because EMG amplitude is influenced by changes in tissue geometry and electrode position relative to the underlying fibers, the normalized EMG amplitude can only be interpreted as a percentage of the muscle activation when normalized with respect to the MVC EMG amplitude estimated for the same muscle length and position. Other methods for normalization are available as normalization to the maximum is not always possible or the best method for some analyses.

Muscle activation vs. EMG amplitude
Muscle activation refers to the number of motor units recruited and their firing rates (i.e., the number of muscle fibers activated and the level at which they are activated). EMG amplitude is the magnitude of the electrical activity of the muscle fibers recorded as the EMG signal. The raw EMG signal is a noise-like signal whose intensity reflects the level of muscle activation. The intensity of the EMG signal is usually measured in terms of its average rectified amplitude. This involves rectifying the raw EMG signal and then low-pass filtering the rectified signal to smooth out the random fluctuations. EMG signals from isometric and constant force contractions can be smoothed more heavily (wider averaging window or lower low-pass filter cut-off frequency) to reduce random noise. EMG signals from dynamic contractions must use a narrower averaging window (or higher cut-off frequency of the low-pass filter) (or higher cut-off frequency of the low-pass filter) in order to track dynamic changes in signal intensity. The information presented in this document generally can be related to the rectified, smoothed EMG signal. This EMG amplitude estimates the intensity of the raw EMG signal at each instant in time and it is often taken as an estimate of the muscle activation, although the relation between EMG amplitude and muscle activation might not be perfectly linear.

Surface vs. intramuscular EMG recordings
EMG recording from intramuscular electrodes may provide a poorer estimate of the muscle activation especially if the recording includes few action potentials, and thus insufficient interference (see Electrode selection matrix (Besomi et al., 2019) for more information).

Matrix surface recordings
Matrix (or array) surface EMG recording samples the signal in many spatial locations and therefore the effect of variations in electrode positioning, which could be compensated by normalization in single channel recordings, can be attenuated without normalization (for example by choosing channels between innervation zone and tendon in all conditions, thus effectively eliminating big variations in amplitude due to electrode position). Nonetheless, all other sources of variability in EMG amplitude would remain in matrix surface EMG. For example, when comparing different subject groups, there would be anatomical differences (e.g., subcutaneous layer thickness, fiber orientation, properties of the electrode-tissue interface [See statement on purpose of normalization]) that would have the same effect in matrix surface EMG as in conventional EMG and that would need to be compensated by normalization also in matrix surface EMG. Therefore, the need for normalization with matrix surface EMG would depend on the experimental question/context. If the same participants are investigated in a longitudinal study, matrix surface EMG may not need normalization as a considerable source of variability in amplitude due to electrode re-positioning can be compensated/attenuated. When comparing different groups, normalization would be needed with matrix surface EMG. In summary, matrix surface EMG may allow analysis of amplitude without normalization in some of the conditions when it would be required for conventional EMG, but not in all.

Within-session considerations
For all normalization methods, it is important to consider features that may change over the course of an experiment that could influence the EMG amplitude, and are not related to changes in muscle activation. Possible issues to consider include environmental (e.g., room temperature, humidity), individual (e.g., skin temperature, sweating) electrode-related (e.g., gel changes over time), and the relationship between the electrodes and source of electrical activity (e.g., movement). These changes may change the accuracy/validity of normalization within a session and would be particularly important to consider for within-session comparisons (e.g. pre vs. post an intervention). EMG amplitude will also change with changes in the amount of amplitude cancellation (e.g. slowing of action potentials). Between-session considerations are included under "Experimental context #2" (see below).

	1. MVC in same task/context as the task of interest *(with matched contraction type*, muscle length/joint*	***2. Standardized isometric MVC*** *(which is not matched to the contraction type*,*	***3. Standardized submaximal task*** *(isometric/ dynamic) that can be task specific.*	***4. Peak/mean EMG amplitude in task***	***5. Non-normalized***	***6. Maximal M-wave amplitude normalization***

(*continued on next page*)

Table 2 (*continued*)

	angle, and/or velocity) **isometric; concentric; eccentric*	*muscle length/joint angle, and/or velocity of the task)*				
General features that should be reported	The instrument used (e.g. isokinetic dynamometer, hand-held dynamometer, manual resistance, chain with a load cell between ankle/wrist and wall, hand-held load cell, torque meters, etc.) and normalization technique. The indication of normalization must be followed by the indication of "with respect to" and the normalization value should be given for an appropriate interpretation of the results. An appropriate justification of the method selected should also be reported. Protocol considerations, such as instruction of the task (e.g., number of repetitions, intensity, hold stable, be precise on target, encouragement when necessary), and any reason to suspect that the maximal contraction might not be achieved (e.g., pain, motivation, fear, distraction, etc.). The indication of the time window over which the EMG amplitude value is calculated. If a low pass filter is used for estimating the "EMG envelope" the filter properties must be reported (e.g., cut off frequency, type and order of the filter). Ideally, the reliability/repeatability of the EMG measure (using whichever methods of normalization/quantification selected) should be reported. Ideally, this should be specific to the muscle(s) and task(s) under investigation. Guidance and familiarization with the task used for normalization, and care to avoid factors that alter amplitude cancellation (e.g. avoid fatigue by using short duration tasks with adequate rest, etc.) will improve its repeatability.					
Definitions *Contraction type*: isometric; concentric; eccentric*	Normalization to an MVC that is matched to the task in terms of joint angle/muscle length, contraction type, and/or joint angular velocity.	Normalization to an isometric MVC that is standardized but not matched to the task under investigation.	Normalization to a standardized submaximal task (i.e., it will not elicit the maximum voluntary activation of a muscle). May or may not be task specific.	Normalization to the mean/peak EMG amplitude from the task under investigation, usually obtained from the peak over trial, but not from MVC trials. One value is used, not a separate value from each trial.	EMG amplitude signal expressed in absolute, non-normalized arbitrary units or raw (milli/micro) Volt (e.g., root mean square [RMS], average rectified value [ARV]).	An M-wave is the compound muscle action potential evoked by electrical stimulation of the motoneurons innervating a muscle.
	General advice: This method is the preferred method for normalization in most contexts and should be used if possible. Accuracy depends on whether the participant has performed a true maximum.	General advice: Although matching of the normalization and task is preferable, this method may be necessary in contexts, but this should be justified and limitations should be reported. Accuracy depends on whether the participant has performed a true maximum.	General advice: This method has *substantial* limitations for interpretation (see Cons below) and should be avoided if possible. Could be appropriate when it is difficult to perform an isolated MVC for the test muscles. Robustness of interpretation will be strengthened by convergence with findings of a second method.	General advice: This method can only be used for specific interpretations of EMG data (e.g., EMG pattern) and is often misused (comparison of amplitude between participant groups).	General advice: This method has substantial limitations for interpretation (see Cons below) and should be avoided if possible.	General advice: This method is used for normalization of evoked muscle responses (e.g. reflex; motor evoked potential). Generally, should not be used for normalization of non-evoked EMG recordings as amount of amplitude cancellation differs for the synchronous activation of motor axons (as occurs in evoked contractions) and voluntary contractions.
	This method includes: Angle and angular velocity specific maximal dynamic/isokinetic/isometric voluntary contraction: The peak EMG amplitude(s) from a maximal voluntary contraction with the same muscle action, joint angle, muscle length, angular velocity or rate of change of muscle length as the task of interest. - The maximum value of the MVCs should be considered. It is preferable to conduct between 3-5 contractions that generate consistent values, with adequate rest periods (1-2 minutes) that will depend on the duration of the maximal efforts. - Could require tailored MVCs for each	This method includes: Non-specific isometric maximal voluntary contraction: The peak EMG amplitude from a maximal isometric voluntary contraction, usually obtained from a mid-range joint angle (not as the task of interest). - The maximum value of the MVCs should be considered. It is preferable to conduct between 3-5 contractions that generate consistent values, with adequate rest periods (1-2 minutes) that will depend on the duration	This method includes: Submaximal isometric voluntary contraction: The peak EMG or mean EMG amplitude from a submaximal isometric/dynamic voluntary contraction against a relative or absolute resistance (e.g., holding a weight with force applied through a pulley or against gravity), in a standardized body position/muscle length. - It is preferable to conduct between 3-5 contractions	This method includes: Peak or mean can be derived from data acquired separately from multiple trials, or from the ensemble average of the multiple trials. Each has different consequences for measured amplitude. Because of the stochastic (random) nature of EMG there will be some variation in the time of peak, and its value, between repeated trials. Measurement of the peak (or mean) from individual trials will preserve the highest amplitudes,		This method includes: The peak-to-peak amplitude of the M-waves (averaged over multiple repetitions), the area under the M-wave (the integral of its absolute value over a given interval) or the average rectified amplitude of the M-wave. - The maximum M-wave (M_{max}) is achieved by supramaximal electrical stimulation of the nerve trunk for the recruitment of all motor units within the motoneuron pool that were depolarized by the stimulus.

(*continued on next page*)

Table 2 (*continued*)

	task or muscle studied, or a maximal dynamic task to normalize specific phases/angles of the muscle(s) studied. - During dynamic contractions, EMG amplitude may change as a function of joint angle due to changes in muscle length and relative position of the electrode with respect to the muscle fibers. The maximum EMG amplitude corresponding to a particular point during the movement, therefore, may be different than the maximum EMG amplitude used for normalization if the MVC is estimated at a different joint angle. - Measuring MVC in <u>non-isometric</u> conditions can be very challenging and always requires a description of such conditions (i.e., contraction type, muscle length, joint angle, and angular velocity).	of the maximal efforts. - Measuring isometric MVC generally requires an instrument that should be either an isometric brace (where the joint is locked) or an isokinetic machine (set for zero velocity). These instruments are important to control testing factors that can influence the output and facilitate the production of maximal contraction. Manual resistance can be acceptable (particularly for single-joint tasks), but requires careful control of movement and the manual resistance must be able to exceed the force generated during the maximal contraction. - If the task is to be used only for normalization of EMG amplitude then the force does not need to be measured/recorded. If the intention is to report these data, the force and moment arm length should be recorded.	that generate consistent values.	ensemble averaging will reduce the peak amplitude as the non-aligned peaks will be averaged out, but may be considered more statistically precise. This may be an issue if the synchronization between peaks differs between participants.		
General considerations	**PROS** - Provides comparator that enables physiological interpretation of EMG amplitude assuming an approximately linear relation with the muscle's potential force output. - More likely to represent true maximum for the experimental context than a standardized isometric MVC that does not match the experimental context. - Although assessment of pattern of activation (e.g. timing of bursts of activity, timing of peak, periods of inactivity, etc.) can be undertaken without normalization, normalization to MVC ***should*** reduce the inter-individual variation in factors that affect EMG amplitude (e.g. electrode orientation, subcutaneous fat, etc.) if the temporal variables are to be selected from an ensemble average of recordings.	**PROS** - Can provide comparator that enables interpretation of EMG amplitude but is more difficult to interpret than an MVC that matches the task features. - This method is faster to implement than method 1 *(MVC in same task/context as the task of interest)*, if the experiment includes multiple contraction types. - Although assessment of pattern of activation (e.g. timing of bursts of activity, timing of peak, periods of inactivity, etc.) can be undertaken without normalization, normalization to MVC ***should*** reduce the inter-individual variation in factors that affect EMG	**PROS** - Provides an alternative to MVC normalization methods if performance of maximum contraction is not possible (e.g., pain, risk of injury, etc.) but requires <u>*substantial*</u> caution for interpretation (see "Cons" below). - Although assessment of pattern of activation (e.g. timing of bursts of activity, timing of peak, periods of inactivity, etc.) can be undertaken without normalization, normalization to submaximal effort ***could*** reduce the inter-individual variation in factors that affect EMG amplitude (e.g. electrode orientation, subcutaneous fat, etc.) if the	**PROS** - Synergies and pattern of activation can be compared. - Although assessment of pattern of activation (e.g. timing of bursts of activity, timing of peak, periods of inactivity, etc.) can be undertaken without normalization, normalization to peak/average in a trial ***will*** reduce inter-individual variation in amplitude if the temporal variables are to be selected from an ensemble average of recordings. - Reduces the inter-subject/inter-muscle differences in amplitude as all are scaled between 0 to 1 if peak is used. - Can easily be recorded (e.g. might be important for	**PROS (and cautions)** - Essentially, comparison of non-normalized EMG is meaningful only when comparison is made between measurements performed on the same muscle and same participant during the same test, under constant environmental conditions (e.g., temperature, humidity), without electrode removal, or when the same electrodes are carefully repositioned in the same locations. An example would be immediately before and after a treatment. - Although not ideal (see "Cons" below), in some contexts the analysis of non-normalized EMG may introduce less error than normalization to a poorly performed MVC or a submaximal task that differs between groups. - May be necessary if MVC is not possible, but interpretation is likely to be strengthened if data are	**PROS** - Provides a measure of the peripheral properties of the neuromuscular system (without involvement of the central nervous system). - Provides comparator that enables interpretation of EMG amplitude, but because an M-wave involves near-synchronous action potentials, its amplitude will be generally higher than voluntary efforts and therefore, is often used for normalizing reflex responses or other responses evoked by electrical or magnetic stimulation (e.g., H-reflexes, motor evoked potentials).

(*continued on next page*)

Table 2 (*continued*)

		amplitude (e.g. electrode orientation, subcutaneous fat, etc.) if the temporal variables are to be selected from an ensemble average of recordings.	temporal variables are to be selected from an ensemble average of recordings.	individuals with specific health conditions [who cannot perform voluntary MVC efforts], children [they might not be cooperative], etc.). - No additional measurement tools are needed	analyzed using several different methods (e.g., also comparison of data normalized to submaximal effort) to test robustness of the interpretation. - May be appropriate to interpret changes in EMG between sessions during MVC efforts (as the task of interest) when normalization would remove any difference. - Although assessment of pattern of activation (e.g. timing of bursts of activity, timing of peak, periods of inactivity, etc.) can be undertaken without normalization, non-normalization means that inter-individual variation in amplitude could be high and if the temporal variables are to be selected from an ensemble average of recordings this would be biased to the individuals with the highest amplitude recordings.	
	CONS - Although this is generally the preferred method for EMG normalization, there are a number of limitations and challenges that need to be considered. - MVC efforts may not be possible in some contexts (e.g., pain, risk of injury, etc.). In that case it is necessary to use alternative methods (e.g., submaximal/ non-normalized). - High variability because success in performing MVC varies within and between participants/ muscles (e.g., systematic difference in capacity to perform MVC between subject groups). - Differences between contraction types are muscle- and task-dependent and should be considered on a case-by-case basis. - Cannot be used to interpret changes in EMG during MVC efforts between sessions, as activity recorded in the MVC will be reflected as 100%, regardless of whether the EMG amplitude has changed (e.g. muscle hypertrophy/atrophy). In this case, consideration of non-normalized EMG or perhaps normalization to the first MVC session can be considered, although this does not account for	**CONS** In addition to considerations for "*MVC in same task/ context*" this method has the following concerns: - EMG recorded in the standardized isometric MVC may differ from that achievable with other contractions types, body positions, muscle lengths, etc. - Position of the electrode relative to the muscle fiber can be different from the task studied.	**CONS** - If performance of the submaximal task differs between groups (e.g., pattern of muscle activation, distribution of activation among muscles), this analysis will be invalid for comparison between groups. - Interpretation with respect to physiology/ mechanism is difficult because the reference value is not relative to the maximum capacity of the muscle. - Systematic differences between groups in performance of the task may be because of pain or could be a feature of the condition (i.e., difference in movement pattern, posture, etc. between groups). - Tasks based on fixed forces/weights will elicit a different relative load and different levels of effort/ activation for different participants. - At a given force it would not be expected that all	**CONS** - EMG amplitude cannot be compared between muscles/ groups as this method makes all signals relative to their peak or mean taken as to 100% (e.g., impossible to distinguish between a muscle that is maximally active or active at 5% of its maximal activation as both will be normalized as 100%). - Value reflects relative difference between tasks/ phases and removes reference to comparable EMG amplitude. - Although this method reduces variation between individuals and between sessions within individuals (because all values are normalized to 100%), it is not possible to identify/ quantify whether the actual peak value differs.	**CONS** - Does not control for factors other than neural drive and muscle activation that impact amplitude (e.g. inter-electrode distance, subcutaneous fat, orientation of the fibers, muscle architecture, etc.). Note that when comparisons are made between participants non-normalization generally leads to random error but not to bias (systematic differences between groups), except when groups differ in ways that would systematically bias the EMG signal, for example group-difference in overlying skinfold thickness. - Subjects with the largest EMG amplitude values can dominate the results of certain statistical tests (e.g., t-tests, ANOVAs).	**CONS** - It is not useful for normalization of non-synchronous activation because it comprises different amounts of amplitude cancellation, which would introduce more error into the analysis. - The repeatability of the maximal M-wave is questionable. - For anatomical reasons it is not possible to generate an M-wave for every muscle (innervating nerve is not accessible for electrical stimulation; short peripheral nerve that does not enable stimulation of nerve without concurrent muscle stimulation). - The electrical stimulation technique (to evoke the M-wave) can cause discomfort for participants. - Special equipment and training are required. - The end-of-fiber component of the signal (non-propagating component) is highly sensitive to changes of the

(*continued on next page*)

Table 2 (*continued*)

	differences in electrode placement, changes in subcutaneous fat, etc. between sessions. - Caution required if MVC is not confirmed (e.g., twitch interpolation can be used to increase confidence of maximum effort). However, this is not always possible (e.g. twitch interpolation is difficult during movement and may not be reliable, electrical stimulation for twitch interpolation is not possible for all muscles [access to nerve/muscle to stimulate; coactivation of synergist muscles]). - Although it is assumed that all muscles that contribute to a task (i.e. all synergist muscles) are active maximally during an MVC, this may not be the case. That is, it is possible that not all muscles that contribute to the force of a task will be activated maximally in that task. - During sustained maximum contractions, MVC usually drops. - Simultaneous recording of force/ torque and EMG signals can help to estimate the time of maximum contraction and whether fatigue is occurring. - It cannot be assured that only the muscle under investigation contributes to the MVC. - Important to note that maximal performance of a task (e.g. maximal pedaling sprint) does not ensure maximal activation of the involved muscles.		muscles contributing to that task are activated to the same proportion of maximum. - If different muscles are recruited to different levels in the submaximal effort this will make between-muscle comparison difficult to interpret. - It cannot be assured that only the muscle under investigation contributes to the submaximal contraction.			muscle–tendon complex relative to the recording electrodes (e.g., geometrical changes, muscle architecture changes). - Difficult to reproduce during dynamic contractions. - Care must be taken with fatigue which will modify the shape and amplitude of the M-wave.
Experimental contexts						
1. Amplitude comparison **within a person and muscle**, between conditions/ tasks (**within a session***). *Without removing electrodes	Yes. <u>EXPLANATION:</u> If the tasks or conditions compared are different (e.g., changes in contraction type, muscle length/joint angle, and/ or velocity), separate normalization methods should be undertaken.	Yes. <u>EXPLANATION:</u> Care with interpretation if the contraction type/muscle length is different between tasks.	Caution. <u>EXPLANATION:</u> Although this method may enable evaluation of differences between tasks, it is essential to consider that unlike MVC normalization, there is no clear indication what the reference value means; the meaning may differ between participants; and the normalization task would not account for potential differences in	Yes. Comparison between *conditions (e.g. treatment)* for a single *task* <u>EXPLANATION:</u> Can be used if one value is used to normalize the measures for a single task across conditions. Caution. Comparison *between tasks*. <u>EXPLANATION:</u> Cannot use a separate maximum value for each task as this would remove any task difference. Use of a	Yes. <u>EXPLANATION:</u> Likely to be acceptable, but care with interpretation if the contraction type/muscle length is different between tasks. This method might be appropriate in some contexts when using matrix surface EMG recordings (see "General considerations for normalization"), but care with interpretation of muscles with anatomical differences.	No. <u>EXPLANATION:</u> Generally only used for normalization of evoked potentials. Nerve stimulation is required to generate an M-wave and is not possible for every muscle.

(*continued on next page*)

Table 2 (*continued*)

			muscle length/contraction type between tasks.	single maximum across tasks requires care with interpretation if the contraction type/muscle length is different between tasks.		
2. Amplitude comparison **within a person and muscle, between sessions** (i.e. re-application of electrodes).	Yes. EXPLANATION: Between-session reliability is likely to be achievable but performance of the MVC task requires consideration. If repeatability of the performance of the MVC effort is poor for the muscle/task of interest this method will impact the normalized EMG amplitude. It This will be critical to consider if factors that are likely to impact the MVC effort vary systematically between sessions (e.g., pain, muscle activity after training, strength, etc.). Methods such as twitch interpolation are possible for some muscles to estimate whether maximal activation has been achieved, but this is not always possible (See CONS above).		Caution. EXPLANATION: Between-session reliability of performance of the submaximal task requires consideration. If it is likely that performance of the submaximal standardized task would vary between days (e.g. as a consequence of performance of a training program) this would add error into the measure - data are required to demonstrate consistency in the standardized task. If an MVC effort cannot be performed reliably, this method might be considered with consideration of the cautions for interpretation.	Generally No. EXPLANATION: Although this method reduces variation between individuals and between sessions within individuals (because all values are normalized to 100%), it is not possible to identify/ quantify whether the actual peak value differs. It is suitable for shape / activation pattern comparisons (see "Identification of pattern of activation from averaged data for comparison between muscles/ group/ trials").	Generally No/Caution EXPLANATION: Differences in electrode placement/ orientation relative to the muscle between sessions will influence EMG amplitude, in a manner that is not possible to quantify. This method might be appropriate in some contexts when using matrix surface EMG recordings (see "General considerations for normalization"). May be the only option to interpret changes in EMG between sessions during MVC efforts (as the task of interest) because normalization to MVC would remove any difference. Needs to be interpreted with caution because it does not control for differences in electrode placement, subcutaneous tissues, etc. between sessions. If an MVC effort cannot be performed reliably, this method might be considered with consideration of the cautions for interpretation.	No. EXPLANATION: As for experimental context #1.
3. Amplitude comparison **between muscles** during the same task (**same** muscle in **different** participants; or **different** muscles in **same** participant)	Yes. EXPLANATION: When the EMG amplitude of a muscle is normalized with respect to the MVC EMG amplitude value of the same muscle, the EMG amplitude of the task of interest can be compared to the same muscle in another participant or another muscle in the same participant to provide information about the relative activation of the muscles. It is important to recognize that relative EMG amplitude does not infer relative force of the muscles. This is because muscles of different size and architecture could have similar relative EMG but different force output (e.g., for a muscle that is smaller, the normalized EMG amplitude may be higher, but generate	Yes. EXPLANATION: In addition to caution for *"MVC in same task/ context"*: Caution if used to normalize activity during contractions of different type (eccentric/ concentric), different muscle length, joint angle, and/or velocity (e.g. EMG amplitude is lower during eccentric than concentric contraction). Interpretation would be difficult if two muscles are operating at different relative length but are normalized to an isometric effort (different fibers / orientation of fibers within recording zone)	No/Generally No. EXPLANATION: Care with interpretation as the activation of the muscles in the submaximal task is unlikely to be equivalent between muscles or groups (e.g., males and females with different relative weight of arms pose a different relative load in the upper body), thus reference value for each muscle will not be standardized. Differences observed between muscles/ participants may be related to either differences in strategies during the tested task or during the submaximal task used to	No. EXPLANATION: Not valid to compare because differences in EMG amplitude between muscles are intentionally removed by the normalization method.	Generally No. EXPLANATION: Requires care with interpretation as electrode issues cannot be perfectly matched (e.g. orientation relative to the muscle fibers; fiber types - larger fiber types = more amplitude cancellation / more fibers active = more amplitude cancellation; thickness of subcutaneous tissue), and systematic bias is likely when comparing between muscles. Can aid interpretation of differences when combined with other analyses to test robustness of interpretation. This method might be appropriate in some contexts when using matrix surface EMG recordings (see "General considerations for normalization"), but care with	No. EXPLANATION: As for experimental context #1.

(*continued on next page*)

Table 2 (*continued*)

	lower absolute force than a larger muscle). Need to consider whether muscles that are being compared are both maximally activated during the MVC task. For example, it may not be possible to elicit maximal activation of a muscle during a particular movement. The normalized EMG amplitude in this case will not represent the relative activation of the muscle with respect to its maximal activation. This may be particularly important for multi-joint tasks, as activation is not necessarily maximal for all muscles. This could be considered as a functional maximum (maximum for the task, but not necessarily the muscle), but needs to be explicitly stated as such when data are reported. Ideally, the EMG amplitude at each position should be normalized with respect to the MVC at that position for each muscle. Note that knowing maximal activation in dynamic tasks is sometimes impossible/ impractical, and other methods should be considered. **For between group comparisons:** Care with interpretation when ability or willingness to perform a true maximum contraction varies between the groups.	standardize values, and this is difficult/not possible to differentiate. Care needs to be taken to consider the anatomical differences among muscles, muscle geometry, subcutaneous tissue thickness, electrode properties etc.		interpretation of muscles with anatomical differences.	
4. Extraction of **muscle synergies** (also called motor modules/ primitives) for **analysis of muscle coordination** (e.g. using methods such as non-negative matrix factorization)	*Note: Muscle synergies analysis is very challenging, and consensus has not yet been reached regarding the physiological information contained within the extracted variables or its interpretation. Until further work is undertaken it is generally advisable to consider normalization to MVC or peak across the task, and interpret the results with caution (i.e., MVC normalization is biased by muscles with large activation, and peak normalization can give "meaning" to muscles that are barely used in a task).				
	Caution. EXPLANATION: The synergy extraction would be biased to describe the muscles that are activated at a high level. As such, it may affect the number of extracted muscle synergies. Ideally, the MVC will be optimized for each muscle considered in the extraction of muscle synergies (i.e., separate MVCs for each muscle, but this may only be possible for isometric contractions).	No. EXPLANATION: In addition to caution described for "*MVC normalization methods*", the activation of the muscles during the submaximal task is unlikely to be equivalent between muscles and between participants (i.e., individual specific muscle activation strategies). This means that the bias within the synergy analysis would differ between individuals and complicate the interpretation of the results.	Caution. EXPLANATION: This method reduces the chance that the data is biased to muscles that are activated at a high level and that the EMG signal of all muscles is equally weighted in the generation of muscle synergies. Caution with muscles that have sustained low-level activation or no activity across the task. In this case, normalization to peak or mean would give unwarranted weighting/	No. EXPLANATION: The synergy extraction would be biased to describe the muscles which exhibit a high EMG amplitude for possible non-relevant reasons (e.g., subcutaneous fat, muscle architecture). This would affect the number of extracted muscle synergies and complicate the interpretation of the results.	No. EXPLANATION: As for experimental context #1.

(*continued on next page*)

Table 2 (*continued*)

			"meaning" of the muscle in the analysis.		
5. Identification of **periods of activity and inactivity** using thresholds based on **signal amplitude** for comparison **between muscles/ groups**.	*Note: some methods estimate ON/OFF activity detection based solely on the resting level of the EMG. For example, ON might correspond to 2–3 standard deviations above the baseline noise, if sustained for a specified number of milliseconds. For this approach, there is no need for amplitude normalization. This method requires establishing a baseline which may vary between groups or muscles, as relaxing a muscle is not always easy/possible. In contrast, when periods of activity/inactivity are identified from values that are expressed as a proportion of a specific EMG amplitude, the amount of muscle activity required to exceeded the threshold will be influenced by the normalization method (i.e., muscle activation required to exceed threshold may differ between muscles if methods other than MVC are used). It is also important to consider the algorithm that is used, and in particular the specific statistical properties of the EMG signal that are utilized.				
	Yes. EXPLANATION: The physiological meaning of the threshold (i.e., percentage of MVC) for onset of EMG will be consistent between muscles and participant groups (as long as maximum contraction is performed and considering the issues raised in experimental context #3. Caution if different level of activation is achieved for different muscles during the attempted MVC.	No. EXPLANATION: If activation in the submaximal task differs between muscles/groups, this will influence the threshold that is set. If percentage of submaximal value is used as the threshold, muscles with low amplitude will have bias towards earlier identification of activity than a muscle that is activated to a high EMG amplitude during the submaximal task.	No. EXPLANATION: As the amplitude of the EMG will likely differ between muscles/groups this will influence the threshold that is set. If percentage of peak/ average value is used as the threshold, muscles with low amplitude will have bias towards earlier identification of activity than a muscle that is activated to a high EMG amplitude during the task.	Caution. EXPLANATION: As the amplitude of the EMG will likely differ between muscles/ groups this will influence the threshold that is set (when periods of activity/ inactivity are identified from values as a proportion of a specific EMG amplitude). If non-normalized value is used as the threshold, muscles with low amplitude will have bias towards earlier identification of activity than a muscle that is activated to a high EMG amplitude during the task.	No. EXPLANATION: As for experimental context #1.
6. Identification of **pattern* of activation** from averaged data for comparison **between muscles/ group/ trials.** *Pattern could relate to timing of events (e.g. time of peak/ trough/onset) or relative amplitude of events or rate of increase/decrease of EMG amplitude, etc.	Identification of features of the pattern* of activity in an EMG trace can be undertaken by using recordings for each single trial in each participant (e.g., time of peak EMG during a task), or from an ensemble average of data from a group of participants. Generally, it is best to quantify features from individual trials because differences in timing of events such as peaks/troughs between participants/trials will lead to smoothing of the data when an ensemble average is performed. When temporal values are calculated from individual trials, EMG amplitude normalization is not required. In some cases, it may be advantageous to generate an ensemble average of the EMG traces for each muscle across participants to provide an overall view of the pattern of EMG. In this case it is important to carefully consider normalization with respect to the question being addressed. This is because EMG traces with larger normalized amplitude will contribute more to the ensemble average than those with small normalized amplitude. If the objective is to consider all traces with equal weight in the average, then normalization to peak (such that all traces are scaled from 0 to 100%) is ideal. If the objective is to retain information of the relative amplitude of EMG (i.e., participants with activation to a greater proportion of MVC would contribute more to the ensemble average) then normalization to MVC may be preferable.				
	Caution. EXPLANATION: The effect of normalization to MVC is that EMG traces with normalized values that are a greater proportion of MVC would contribute more to the ensemble average (and converse).	No. EXPLANATION: The effect of normalization to a submaximal effort is that EMG traces with normalized values that are a greater proportion of the submaximal task would contribute more to the ensemble average (and converse), and the activation of the muscles during the submaximal task is unlikely to be equivalent between muscles and between participants. This means that the bias would differ between individuals and complicate the interpretation of the results.	Caution. EXPLANATION: Normalization to peak results in equal weighting of each muscle/participant to the average. One limitation of this approach is that EMG signals that are very low in amplitude (e.g. due to a low level of muscle activation or poor quality of EMG recordings), if normalized to their peak value during the task will incorrectly appear to be very active throughout. As there is no reference to a consistent intensity of activity, estimate of rate of change of EMG would differ between muscles.	No. EXPLANATION: When generating an ensemble average across participants the use of non-normalized data would bias the result to the muscle with the largest signal, which may be caused by other non-relevant reasons (e.g. subcutaneous fat, muscle architecture).	No. EXPLANATION: As for experimental context #1.

(continued on next page)

Table 2 (*continued*)

7. Comparison of force between muscles/ groups from only the EMG amplitude (in the absence of EMG-force models)	It is not possible to estimate force from the normalized EMG amplitude of a muscle(s) alone. As many muscles act on a joint, force generated by an individual muscle cannot be directly measured from external force, and can only be estimated from EMG-force models (see experimental context #9) (unless specialized methods are used such as a force transducer in the individual muscle tendon). Relationship between EMG and force is not always clear (affected by many factors – muscle contraction type and speed, muscle length, muscle size, spatial order of recruitment of motor units, the contribution of force by other muscles, etc.), and measures of the force-EMG relationship are not always possible. The force produced by a muscle depends on its activation and biomechanical factors, such as its physiological cross-sectional area, specific tension, and force-length and force-velocity relationship. Comparison of force output between muscles or groups needs to consider all of these factors that are often not possible to estimate in vivo.					
	No. EXPLANATION: Normalization to MVC indicates the amount of activation relative to its maximal potential activation, but not the muscle's capacity to generate force (i.e., a small and large muscle can both be activated to 100% but produce vastly different forces). In conjunction with other information (e.g. the muscle's physiological cross-sectional area, etc.) measures of a muscle's activation as a proportion of its maximum potential activation may provide important information about the proportion of potential force that is generated in a task. This may be relevant, depending on the question that is being addressed.		No. EXPLANATION: Normalization to a submaximal contraction indicates the amount of activation relative to its activation in that task but provides no information regarding the muscle's capacity to generate force.	No. EXPLANATION: EMG amplitudes cannot be compared between muscles/ groups as this method makes all signals relative to their peak or mean taken as to 100% (e.g., impossible to distinguish between a muscle that is active at MVC and 5% MVC as both will be normalized as 100%).	No. EXPLANATION: Does not control for factors other than muscle activation that impact amplitude (e.g., inter-electrode distance, subcutaneous fat, orientation of the fibers etc.). This method does not consider muscle force-generating capacity.	No. EXPLANATION: This method indicates the level of activation relative to its maximal potential activation with near-synchronized motor unit discharge, but not the muscle's capacity to generate force.
8. Interpretation of **changes in force** (from the EMG amplitude) contributed by a muscle **between phases of dynamic task** for a single muscle.	Relationship between EMG and force is not always clear, and force produced by a muscle at a given level of EMG will differ depending on the length and velocity at which it operates. Estimation of changes in net torque at a joint may be inaccurate if EMG is recorded from one/few muscles, because net force depends on all synergists and antagonists. During a dynamic task, the joint angle and thus the relative contribution of different muscles to the total force generated may change, i.e. the biomechanics also needs to be considered. Contributions of other muscles may be more prone to change in a dynamic contraction. This can be controlled to some degree by measuring EMG from other relevant muscles. For EMG-force model recommendations see experimental context #9.					
	Caution EXPLANATION: If contraction type differs between phases this may require separate normalizations. Normalization process should be conducted for each type of contraction or phase (see "definitions"). The outcome will not be a quantitative estimate, just an estimate of the direction of the change	No. EXPLANATION: Maximum EMG amplitude will differ with contraction type/muscle length/etc., and preclude any interpretation of difference in estimated force.	No. EXPLANATION: EMG amplitude will differ with contraction type/muscle length/etc., and preclude any interpretation of difference in estimated force.			No. EXPLANATION: This method indicates the level of activation relative to its maximal potential activation with synchronized motor unit discharge, but not the muscle's capacity to generate force.
9. EMG-informed modeling (biomechanical models).	When used in modeling, the primary goal of normalization of the EMG signal is to help resolve the muscle redundancy problem (i.e., many muscles contribute to the generation of moments at a joint, and for modeling it is necessary to estimate the relative contribution of each muscle to the net joint moment). There are 2 main forms of modeling; modeling that takes into account muscle properties and models that use system identification. In both cases, the EMG signal is used as an input to estimate the muscle activation, which is then typically used in a muscle model to predict force. For models that take into account the muscle anatomy (physiological cross-sectional area, muscle fiber length), force-velocity relationship, and length-tension relationship, normalization methods will provide an estimate of the muscle activation, but limitations should be considered as outlined in experimental contexts #2–3, above. System identification and other input/output modeling approaches can be used to build subject-specific models, for example to control prosthetic devices. Normalization is typically not a concern when measures of EMG amplitude are used as inputs to these models because the process of estimating model parameters inherently performs any normalization needed to describe the optimal input/output relationships.					
	Caution. EXPLANATION: Refer to explanation for experimental context 2 & 3. In general, this approach is appropriate for the specific task in which the MVC is conducted but might not produce	Caution. EXPLANATION: Refer to explanation for experimental context 2 & 3. This method is commonly performed to achieve a maximum activation across	No. EXPLANATION: Normalization to an arbitrary activity loses all information about force production, as the force in the arbitrary activity is	No EXPLANATION: As for *"Standardized submaximal task"* method.	Caution. EXPLANATION: Refer to explanation for experimental context 2 & 3. This method can be used if the general shape and timing of the muscle activation is the primary objective	No. EXPLANATION: As for experimental context #1.

(*continued on next page*)

Table 2 (*continued*)

	reasonable estimates across a broad range of tasks and should be used with caution. If the model takes into account the muscle anatomy, force velocity relationship, and length-tension relationship, this method is the appropriate procedure when applied at optimum length and isometrically.	muscle groups and provides a general estimate of maximal activation but does not necessarily match the tasks. If the model takes into account the muscle anatomy, force velocity relationship, and length-tension relationship, this method is the appropriate procedure when applied at optimum length and isometrically.	unknown (force may be known in some cases). Scaling of EMG amplitude to force is based on anatomical/ mechanical considerations requiring EMG normalized to an isometric MVC or it is optimized by model fitting in which case normalization is unnecessary.		and not the absolute magnitude. Numerical optimization is necessary to scale the magnitude of the activation to best-match the net joint moment.	
10. Evoked responses (e.g., submaximal and maximal M-Wave, transcranial magnetic stimulation H-reflex).	Caution. No. EXPLANATION: Refer to explanation for experimental context 1-3. Does not involve synchronized discharge of entire motor unit pool.					Yes. EXPLANATION: This is the usual method used to normalize evoked potentials. Provides a method to express the response of the motor units that are recruited by the stimulation as a percentage of the recording of the entire motor unit pool reflected by the M-wave. Controls for changes in the peripheral neuromuscular components. Important to consider that recordings do not always represent the entire motor unit pool and that the amount of synchronization of motor units depends on the stimulus type (e.g. stimulation of the peripheral nerve vs. transcranial magnetic stimulation). Rather than maximum M-wave it is possible to track to a fixed percentage (e.g., threshold tracking methods for both M-wave and H response). Note sometimes it is not needed to normalize the H-reflex to M-max, as it depends on the question (e.g., Comparison of M-max between conditions within a session).

(*continued on next page*)

Table 2 (*continued*)

Frequently asked questions	1. How do I compare the EMG amplitude between groups (e.g., between sex, injured/non-injured, etc.)? – see Experimental context #3 2. How do I compare EMG amplitude before and after treatment/exercise in the same group of subjects? - Recommendations for comparison of the EMG amplitude pre- and post- an intervention are shown in Experimental context #1 (within a session) and #2 (between sessions). 3. How do I compare forces before and after treatment/exercise in the same group of subjects? - Comparisons of muscle force and joint torque are not possible when only the EMG amplitude from a muscle(s) is considered. Biomechanical models should be considered to answer these experimental questions (see experimental context #9). 4. How do I measure and compare EMG amplitude measured in different conditions? (e.g., isometric, concentric, eccentric, different body positions, etc.) – see Experimental context #3. 5. How do I know when a muscle is relaxed? – For muscles parallel to the skin, the relaxed muscle can be determined when no propagating potentials are detectable, but this requires a matrix of surface electrode (with at least one electrode row) for motor units that are relatively superficial, and would not apply to pennate muscles (e.g., gastrocnemius). An intramuscular recording method could be required for deeper muscles/motor units. From a practical point of view, in order to establish a baseline noise level or to ensure adequate rest between trials or to establish an appropriate initial condition for a trial, the EMG signal should be as small as possible. 6. How can I compare EMG amplitude between trials/participants if interventions change/affect the relationship between EMG amplitude and muscle activation? (e.g., fatiguing exercise) – depends on the question being asked, if the question is "can the muscle be activated to the same proportion of its maximum after fatigue" then the unfatigued MVC can be used as reference (normalization) to estimate the overall degree of activation.

specific, (4) Peak/mean EMG amplitude in task, (5) Non-normalized EMG amplitude, and (6) Maximal M-wave amplitude normalization. The matrix was reviewed by the nominated CEDE members to obtain feedback on the proposed design and content features of the initial draft. This process was followed by refinement of the content and further development before progressing to the Delphi process.

The overall format for this matrix was divided into six sections: general considerations for amplitude normalization, general features that should be reported, pros and cons of each method, common experimental contexts, and frequently asked questions. For each experimental context, a recommendation of the appropriateness of an EMG amplitude normalization method for a specific application was provided as "yes", "caution", "generally no", or "no" (see Table 1 for definitions), along with an explanation.

2.2. Delphi process to reach consensus of the content

An online Delphi approach was used to reach consensus among experts. This approach is a widely accepted method to achieve consensus and is used as a decision-making method (Waggoner et al., 2016). The Delphi technique uses multiple rounds of questionnaires that can involve allocation of ratings and/or open-ended answers (von der Gracht, 2012). In round one, the entire matrix was sent to the whole CEDE team (n = 20) along with the instructions and timeline for completion. A reminder was emailed after two and four weeks. The same approach and timeline were used for the subsequent round. For the assessment of satisfaction level and agreement/disagreement among participants, a nine-point Likert scale was used (Fitch et al., 2001) that asked contributors to indicate that they considered that content was "appropriate" (score 7–9), "uncertain" (score 4–6) or "inappropriate" (score 1–3). Participants rated their agreement for each cell of the matrix and were invited to provide comments to highlight aspects that were not agreeable. Consensus was considered to be reached if $>$ 70% of contributors provided scores between 7 and 9 (appropriate) and $<$ 15% of contributors provided scores between 1 and 3 (inappropriate) (Williamson et al., 2012). As a further criterion, an interquartile range (IQR) $\leq$ 2 units on a nine-unit scale was necessary to consider that consensus had been reached among Delphi panelists (von der Gracht, 2012). For cells that reached consensus, any contributor's comments that were recorded were considered and implemented as necessary.

Based on the results of round one, items with an insufficient consensus were refined by the steering committee by integrating feedback, and were re-sent to the experts who had provided ratings below 7 points. Changes or new information proposed by contributors were highlighted in the second-round questionnaire. All CEDE members reviewed the final document for endorsement and were included as authors. For this matrix, 20 experts participated in the Delphi process. The lead investigator (PH) and the coordinator (MB), who developed the draft matrix, did not participate in that process, but in addition to developing the initial content, they oversaw the project and collected/integrated all responses.

All data were entered and processed with Microsoft Excel. The number and percentage of participants rating each outcome as appropriate (score 7–9), uncertain (score 4–6) and inappropriate (score 1–3) were calculated, as well as the median and IQR for each item.

3. Results

From the 20 experts who agreed to participate in the Delphi process, 18 (80%) replied to the first-round questionnaire. Version 1 was composed of 19 items. After round one, nine sections were ranked with insufficient consensus. For round two, the nine sections were re-sent to experts who had rated an item lower than 7 points (n = 13). Of those, 12 experts (92.3%) completed the second-round questionnaire. All sections reached consensus after this round. A summary of the results of the two rounds of the Delphi consensus process is presented in Appendix 1 and 2, respectively.

Table 3
Checklist* for EMG amplitude normalization matrix.

Section/topic	Item	Description of item	Reported (Yes/No/NA)	Considerations/ limitations reported on page #
Amplitude normalization	1	Is the normalization method (and instrumentation used, if applicable) reported?		
	2	Is the selected normalization approach appropriate/valid for the question to be addressed? *If not, are the limitations and justification for the selection of the normalization approach described in the paper?*		
	3	Is the protocol for the normalization procedure reported with sufficient detail? This should at least include: - Instruction of the task; - Methods used to confirm that the task used for normalization is performed accurately or any reason to suspect that the maximal contraction might not be achieved.		
	4	Are familiarization and guidance procedures with the task used for normalization performed?		
	5	Is the time window (over which the EMG amplitude value is calculated) reported?		
	6	If applicable, are the filter properties (e.g., cut off frequency, type and order of the filter) reported?		
	7	Is the reliability/repeatability of the EMG measure reported? *If not, are potential limitations outlined in the paper?*		

Legend: *This checklist is formatted for use in preparing and reviewing manuscripts that include EMG.
NA: Not applicable.

The EMG amplitude normalization matrix endorsed by the CEDE project team is presented in Table 2. A checklist (Table 3) is provided to guide and facilitate the reporting of EMG normalization based on the content of the matrix.

4. Discussion

The matrix developed in this Delphi consensus project represents a summary of recommendations of six methodological approaches for normalization of EMG amplitude. Ten experimental contexts that represent common questions that are asked in research and clinical application of EMG were included. For each context, a recommendation is provided with different levels of certainty.

Strengths and limitations of this consensus process have been described in detail elsewhere (Besomi et al., 2019). In brief, the matrix represents a concise overview of common normalization methods and its application in different situations, as well as recommendations based on expert consensus opinion. Updates of this matrix will be needed as new empirical data emerge and as new methods become available. Because empirical data are not always available, some recommendations are based on logical and theoretical considerations.

Within the consensus process, there were some conflicting opinions between experts regarding the use of some normalization methods for specific applications. The greatest concern related to how to make decisions when the ideal method cannot be implemented. For instance, in participants with pain, it is commonly considered that participants may be unable or unwilling to perform a maximal effort. In that case, normalization to MVC is likely to be biased towards higher resulting values, variable and invalid. In some cases there is no method available to answer the research question (e.g., when participants cannot voluntarily activate a muscle [e.g., motor paralysis after cerebrovascular accident] or have difficulty activating the muscle [e.g., pelvic floor muscle activation in urinary incontinence, or pediatric population]). In those cases, where no ideal method is available, interpretation of the EMG amplitude may depend on the use of multiple sub-optimal methods, and consideration the convergence/divergence arising from these. When the task of interest *is* a maximum effort, normalization to MVC is not possible. In that case, non-normalized EMG amplitude may be considered with caution, but may require concurrent analysis of biomechanical parameters (e.g., physiological cross-sectional area and muscle fiber length) to interpret a difference or change within and between participants.

Some normalization methods are commonly used inappropriately, which leads to misleading interpretations and recommendations. For example, it has been proposed that normalization of EMG amplitude in a standardized submaximal task enables comparison between groups when an MVC is not possible. Unfortunately, the likelihood that participants in the groups perform the normalizing task in a manner that differs between groups, it renders this form of analysis invalid (Hug & Tucker, 2017). If this method is used, this limitation upon the interpretation of data should be considered and discussed. Further, normalization to the peak or average amplitude in a task does not enable comparison of amplitude between groups or muscles. This method only reflects how the amplitude is distributed across the task and would remove differences between individuals with high and low activation.

A critical issue highlighted in this consensus process is that the ideal normalization method may be muscle- and task-dependent (Ball and Scurr, 2013). EMG amplitude recorded during MVCs differs as a function of joint angle (i.e., muscle length) (Worrell et al., 2001) and shortening/lengthening velocity (Buckthorpe et al., 2012). Normalization methods require careful consideration when dynamic tasks are being assessed.

5. Conclusion

This matrix presents recommendations for the selection of EMG normalization methods, developed by the CEDE project team. Its aim is to improve the quality of the reporting and interpretation of EMG amplitude data. This matrix includes six commonly used approaches for amplitude normalization along with their definitions, pros and cons, and consideration of the experimental contexts in which they are used commonly. This matrix does not replace formal training or education in EMG practice. Rather, it is intended for use as a reference when planning studies, and when reporting (and justifying) the decisions that are made in selecting EMG amplitude normalization methods. EMG normalization is a major issue that should be planned *before* data collection to ensure that the appropriate tasks are implemented and conducted, to enable valid methods of data analysis.

Statements

Funding: This research was funded by the National Health and Medical Research Council (NHMRC) of Australia (Program Grant: APP1091302). PWH is supported by an NHMRC Senior Principal Research Fellowship (APP1102905). MB is supported by the University of Queensland Research Training Scholarship. MCK was supported by the NHMRC Program Grant (APP1132524), Partnership Project (APP1153439) and Practitioner Fellowship (APP1156093). AH is supported by Slovenian Research Agency (projects J2-1731 and L7-9421 and Program funding P2-0041). FH is supported by a fellowship from the Institut Universitaire de France (IUF). DF is supported by the European Research Council (ERC; 810346) and by the Royal Society (Wolfson Research Merit Award).

Declaration of Competing Interest

None declared.

Appendix 1. Round One Rating Scores. Each cell provides median score and IQR (in parenthesis) in first row, then % appropriate (scores 7–9) followed by inappropriate (scores 1–3) in second row.

Amplitude normalization matrix items – ROUND 1	*1. MVC in same task/ context as the task of interest*	*2. Standardized isometric MVC*	*3. Standardized submaximal task*	*4. Peak/mean EMG amplitude in task*	*5. Non-normalized*	*6. Maximal M-wave amplitude*
General considerations for normalization	7 (1.5) / 72.2%, 0%					
General features that should be reported	7 (1.8) / 72.2%, 0%					
Definitions	8 (1.8) 77.8%, 0%	8 (1.8) 77.8%, 0%	8 (1.8) 88.9%, 5.6%	7.5 (**2.8**) 72.2%, 5.6%	9 (1) 94.4%, 0%	7.5 (2) 83.3%, 5.6%
General considerations - PROS	8 (1) 83.3%, 0%	8 (1) 88.9%, 0%	8 (2) **66.7%,** 0%	8 (0) 83.3%, 0%	8 (1) 88.9%, 0%	8 (1) 83.3%, 5.6%
General considerations - CONS	8 (2.8) 72.2%, 0%	8 (1) 99.4%, 0%	8 (1) 99.4%, 0%	8 (1) 83.3%, 0%	8 (1) 94.4%, 0%	8 (1.8) 77.8%, 11.1%
Experimental contexts						
1. Amplitude comparison between muscles within a person.	8 (3) **66.7%,** 0%	8 (1.8) 83.3%, 0%	8.5 (1.8) 83.3%, 0%	9 (1) 88.9%, 0%	8 (1.8) 83.3%, 0%	8 (1) 83.3%, 5.6%
2. Amplitude comparison of a muscle between participant groups.	8 (3) **66.7%,** 11.1%	8 (2) 77.8%, 5.6%	8 (2.8) 72.2%, 11.1%	8 (2) 77.8%, 5.6%	8 (**2.5**) 72.2%, 11.1%	8 (**2.5**) 72.2%, 5.3%
3. Amplitude comparison within a person and muscle, between conditions/ tasks (within a session)	8 (2) 88.9%, 0%	8 (1.8) 94.4%, 0%	8 (2) 88.9%, 0%	8 (1.8) 88.9%, 5.6%	8 (1.8) 83.3%, 5.6%	8 (1) 83.3%, 5.6%
4. Amplitude comparison within a person and muscle, between sessions (i.e. re-application of electrodes)	8.5 (1) 88.9%, 0%	8.5 (1) 88.9%, 0%	8 (2) 77.8%, 0%	8 (**2.8**) 72.2%, 5.6%	8 (**2.8**) 72.2%, 11.1%	8 (1.8) 77.8%, 5.6%
5. Extraction of muscle synergies (also called motor modules/ primitives) for analysis of muscle coordination	8 (**2.8**) 88.9%, 5.6%	8 (2) 77.8%, 5.6%	8 (**2.8**) 72.2%, 0%	8 (2) 72.2%, 0%	8 (2) 83.3%, 0%	8 (1.8) 88.9%, 0%
6. Identification of periods of activity and inactivity using thresholds based on signal amplitude for comparison between muscles/ groups.	8 (**2.5**) 72.2%, 0%	8.5 (1) 77.8%, 0%	8 (**3**) **61.1%,** 5.6%	8 (**2.8**) **66.7%,** 5.6%	8 (**2.8**) **66.7%,** 5.6%	8 (**2.8**) 72.2%, 0%
7. Identification of pattern* of activation from averaged data between muscles/ group/ trials	8 (1) 88.9%, 0%	8 (1) 88.9%, 0%	8 (2) 77.8%, 0%	8 (**2.5**) 72.2%, 0%	8 (1.8) 83.3%, 0%	8 (1) 83.3%, 5.6%
8. Comparison of force between muscles/groups.	8.5 (1.8) 77.8%, 0%	9 (1.8) 83.3%, 0%	9 (1.8) 83.3%, 0%	9 (1.8) 83.3%, 0%	8.5 (2) 83.3%, 0%	9 (1.8) 83.3%, 0%
9. Interpretation of changes in force contributed by a muscle between phases of dynamic task for a single muscle.	8 (**2.8**) 72.2%, 5.6%	8.5 (1.8) 83.3%, 5.6%	8.5 (2) 83.3%, 5.6%	8.5 (1.8) 83.3%, 5.6%	8.5 (1.8) 83.3%, 5.6%	8.5 (1.8) 83.3%, 5.6%
10. EMG-informed modeling	8 (1.8) 77.8%, 0%	8 (1) 77.8%, 0%	8 (**2.5**) 72.2%, 0%	8 (1.8) 83.3%, 0%	8 (2) 77.8%, 5.6%	8 (**2.8**) 72.2%, 5.6%
11. Evoked responses (e.g., H-reflex)	9 (1) 83.3%, 0%	9 (1) 83.3%, 0%	9 (1) 83.3%, 0%	9 (1) 83.3%, 0%	9 (1) 83.3%, 0%	7 (1.8) 83.3%, 0%
Frequently asked questions	7 (1.8) 72.2%, 0%					

Legend: Numbers in bold represent items that did not reach consensus.

Appendix 2. Round Two Rating Scores. Each cell provides individual responses in first row, median score and IQR (in parenthesis) in second row, then % and ratio (in parenthesis) of appropriate (scores 7–9) followed by % of inappropriate (scores 1–3) in third row.

Amplitude normalization matrix items – ROUND 2	*1. MVC in same task/ context as the task of interest*	*2. Standardized isometric MVC*	*3. Standardized submaximal task*	*4. Peak/mean EMG amplitude in task*	*5. Non-normalized*	*6. Maximal M-wave amplitude*
Definitions (n = 7/8)	99 88888 8 (0.5) 100% (7/7), 0%	999 888 7 8 (1) 100% (7/7), 0%	99 888 77 8 (1) 100% (7/7), 0%	999 888 7 8 (1) 100% (7/7), 0%	999 8888 8 (1) 100% (7/7), 0%	99 8888 7 8 (0.5) 100% (7/7), 0%
General considerations – PROS (n = 6/7)	99 888 7 8 (0.8) 100% (6/6), 0%	99 888 7 8 (0.8) 100% (6/6), 0%	9 888 7 5 8 (0.8) 83.3% (5/6), 0%	999 888 8.5 (1) 100% (6/6), 0%	999 8 6 **4** 8.5 **(2.5)*** 66.7% (4/6), 0%	999 888 8.5 (1) 100% (6/6), 0%
Experimental contexts						
2. Amplitude comparison within a person and muscle, between sessions (i.e. re-application of electrodes) (n = 7/8)	99 8888 7 8 (0.5) 100% (7/7), 0%	99 888 7 4 8 (1) 85.7% (6/7), 0%	9 888 7 66 8 (1.5) 71.4% (5/7), 0%	99 88 77 3 8 (1.5) 85.7% (6/7), 16.7%	999 8 7 5 **3** 8 **(3)*** 71.4% (5/7), 16.7%	999 888 7 8 (1) 100% (7/7), 0%
3. Amplitude comparison between muscles during the same task (same muscle in different participants; or different muscles in same participant) (n = 5/6)	999 88 9 (1) 100% (5/5), 0%	999 88 9 (1) 100% (5/5), 0%	99 88 6 8 (1) 80% (4/5), 0%	999 88 9 (1) 100% (5/5), 0%	9 8888 8 (0) 100% (5/5), 0%	999 8 5 9 (1) 80% (4/5), 0%
4. Extraction of muscle synergies (also called motor modules/ primitives) for analysis of muscle coordination (n = 6/7)	9999 8 7 9 (0.8) 100% (6/6), 0%	99999 7 9 (0) 100% (6/6), 0%	9999 8 7 9 (0.8) 100% (6/6), 0%	9999 8 7 9 (0.8) 100% (6/6), 0%	99999 8 9 (0) 100% (6/6), 0%	9999 88 9 (0.8) 100% (6/6), 0%
5. Identification of periods of activity and inactivity using thresholds based on signal amplitude for comparison between muscles/ groups (n = 4/5)	99 88 8.5 (1) 100% (4/4), 0%	99 88 8.5 (1) 100% (4/4), 0%	99 88 8.5 (1) 100% (4/4), 0%	99 88 8.5 (1) 100% (4/4), 0%	99 88 8.5 (1) 100% (4/4), 0%	99 88 8.5 (1) 100% (4/4), 0%
6. Identification of pattern of activation from averaged data for comparison between muscles/ group/ trials (n = 7/8)	9999 888 9 (1) 100% (7/7), 0%	99999 88 9 (0.5) 100% (7/7), 0%	9999 888 9 (1) 100% (7/7), 0%	999 888 7 8 (1) 100% (7/7), 0%	99999 88 9 (0.5) 100% (7/7), 0%	99999 88 9 (0.5) 100% (7/7), 0%
8. Interpretation of changes in force (from the EMG amplitude) contributed by a muscle between phases of dynamic task for a single muscle (n = 3/4)	99 7 9 (1) 100% (3/3), 0%	99 7 9 (1) 100% (3/3), 0%	99 7 9 (1) 100% (3/3), 0%	99 7 9 (1) 100% (3/3), 0%	99 7 9 (1) 100% (3/3), 0%	99 7 9 (1) 100% (3/3), 0%
9. EMG-informed modeling (biomechanical models) (n = 4/5)	999 7 9 (0.5) 100% (4/4), 0%	999 7 9 (0.5) 100% (4/4), 0%	999 7 9 (0.5) 100% (4/4), 0%	999 7 9 (0.5) 100% (4/4), 0%	999 7 9 (0.5) 100% (4/4), 0%	999 7 9 (0.5) 100% (4/4), 0%

Legend: The content of two sections in the first-round questionnaire (experimental contexts 1 and 2), was merged into one for the second-round questionnaire (experimental context 3).

* Although these items presented IQR > 2, it was decided that these sections would not follow to a third round. The specific content of concern to the two CEDE members related to the suggestion that normalization was not needed when matrix or array surface EMG electrodes are used. A new paragraph within "General considerations" (the first section of the matrix) was added to clarify this issue with the input of selected CEDE experts, and these edits/additions were confirmed with the two contributors for their endorsement.

References

Albertus-Kajee, Y., Tucker, R., Derman, W., Lamberts, R.P., Lambert, M.I., 2011. Alternative methods of normalising EMG during running. J. Electromyogr. Kinesiol. 21 (4), 579–586.

Ball, N., Scurr, J., 2013. Electromyography normalization methods for high-velocity muscle actions: review and recommendations. J. Appl. Biomech. 29 (5), 600–608.

Besomi, M., Hodges, P.W., Van Dieën, J., Carson, R.G., Clancy, E.A., Disselhorst-Klug, C., ... Wrigley, T., 2019. Consensus for experimental design in electromyography (CEDE) project: Electrode selection matrix. J. Electromyogr. Kinesiol. 48, 128–144.

Bolgla, L.A., Uhl, T.L., 2007. Reliability of electromyographic normalization methods for evaluating the hip musculature. J. Electromyogr. Kinesiol. 17 (1), 102–111.

Buckthorpe, M.W., Hannah, R., Pain, T.G., Folland, J.P., 2012. Reliability of neuromuscular measurements during explosive isometric contractions, with special reference to electromyography normalization techniques. Muscle Nerve 46 (4), 566–576.

Burden, A., 2010. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. J. Electromyogr. Kinesiol. 20 (6), 1023–1035.

Farina, D., Merletti, R., Enoka, R.M., 2004. The extraction of neural strategies from the surface EMG. J. Appl. Physiol. 96 (4), 1486–1495.

Farina, D., Merletti, R., Enoka, R.M., 2014. The extraction of neural strategies from the surface EMG: an update. J. Appl. Physiol. 117 (11), 1215–1230. https://doi.org/10.1152/japplphysiol.00162.2014.

Fitch, K., Bernstein, S.J., Aguilar, M.D., Burnand, B., LaCalle, J.R., Lazaro, P., van het Loo, M., McDonnell, J., Kahan, J.P., 2001. The Rand/UCLA appropriateness method user's manual. Santa Monica, CA: RAND Corporation.

Hermens, H.J., Freriks, B., Disselhorst-Klug, C., Rau, G., 2000. Development of recommendations for SEMG sensors and sensor placement procedures. J. Electromyogr. Kinesiol. 10 (5), 361–374.

Hodges, P.W., 2019. Editorial: consensus for experimental design in electromyography (CEDE) project. J. Electromyogr. Kinesiol. 50, 102343.

Hug, F., Tucker, K., 2017. Surface electromyography to study muscle coordination. In: Müller, B., Wolf, S.I., Brueggemann, G.-P., Deng, Z., McIntosh, A., Miller, F., Selbie, W.S., (Eds.). Handbook of Human Motion. Cham: Springer International Publishing, pp. 1–21.

Merletti, R., 2014), pp.I-II.. Standards for reporting EMG data. J. Electromyogr. Kinesiol. 24 (2) I-II.

Merlo, A., Campanini, I., 2016. Applications in movement and gait analysis. In: Merletti, R., Farina, D., editors. Surface Electromyography: Physiology, Engineering, and Applications. Chapter 16, pp. 440–59.

Murley, G.S., Menz, H.B., Landorf, K.B., Bird, A.R., 2010. Reliability of lower limb electromyography during overground walking: a comparison of maximal- and sub-maximal normalisation techniques. J. Biomech. 43 (4), 749–756.

Raez, M.B.I., Hussain, M.S., Mohd-Yasin, F., 2006. Techniques of EMG signal analysis: detection, processing, classification and applications. Biol. Proced Online 8, 11–35.

Staudenmann, D., Roeleveld, K., Stegeman, D.F., van Dieen, J.H., 2010. Methodological aspects of SEMG recordings for force estimation–a tutorial and review. J. Electromyogr. Kinesiol. 20 (3), 375–387.

Tabard-Fougere, A., Rose-Dulcina, K., Pittet, V., Dayer, R., Vuillerme, N., Armand, S., 2018. EMG normalization method based on grade 3 of manual muscle testing: Within- and between-day reliability of normalization tasks and application to gait

analysis. Gait Posture 60, 6–12.
von der Gracht, H.A., 2012. Consensus measurement in Delphi studies: Review and implications for future quality assurance. Technol Forecast Soc. 79 (8), 1525–1536.
Waggoner, J., Carline, J.D., Durning, S.J., 2016. Is there a consensus on consensus methodology? Descriptions and recommendations for future consensus research. Acad. Med. 91 (5), 663–668.
Williamson, P.R., Altman, D.G., Blazeby, J.M., Clarke, M., Devane, D., Gargon, E., Tugwell, P., 2012. Developing core outcome sets for clinical trials: issues to consider. Trials. 13 (1), 132.
Worrell, T.W., Karst, G., Adamczyk, D., Moore, R., Stanley, C., Steimel, B., Steimel, S., 2001. Influence of joint position on electromyographic and torque generation during maximal voluntary isometric contractions of the hamstrings and gluteus maximus muscles. J. Orthop. Sports Phys. Ther. 31 (12), 730–740.

Manuela Besomi is a PhD candidate at The University of Queensland. She received her Bachelor degree in Physiotherapy (Universidad del Desarrollo, Chile) and completed her MPhil degree in Clinical Epidemiology at Universidad de La Frontera (Chile) in 2016. Her current PhD project involves shear wave elastography, electromyography, biomechanics and physical tests to understand whether novice runners with iliotibial band syndrome and patellofemoral pain move and use muscles differently than people without the condition.